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SIMULATING COST AND QUALITY IN WATER DISTRIBUTION

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ABSTRACT: A spatial approach that disaggregates the water supply system into the components of acquisition-treatment and transmission-distribution, allows these components to be studied in isolation and in combination. Each of these components has different cost and physical functions and the cost and performance trade-offs between these functions can provide important insights into regionalization and cost-related issues. The Water Supply Simulation Model (WSSM) described in this paper is a system of computer programs that allows for an evaluation of the physical and economic characteristics of a water distribution system in a spatial framework. The development of the model and its application to a case study situation is presented.

INTRODUCTION

Passage of the Safe Drinking Water Act has intensified interest in problems related to water supply and water utility management. Economic analysis of the regulations to be promulgated under the Act indicates that there may be adverse effects on some water utilities (1). This effect may be most pronounced in small utilities. An option often suggested is for small systems to combine or join with another larger system to form a regional water supply utility. The economies of scale associated with a regional water system would supposedly benefit small system consumers.

A characteristic of many production and transportation problems is the trade-off between the cost of building and operating facilities to meet demands for a product, and cost of transportation (8). High transportation costs and low facility costs imply decentralization; the reverse implies a few large central facilities. These same characteristics must be considered in planning, designing, constructing and operating water supply systems.

Physically, it is possible to separate the water supply system into two components: (1) The acquisition and treatment function; and (2) the delivery (transmission and distribution) system (3). Each of these components has a different cost function. The unit costs associated with treatment facilities are usually assumed to decrease as the quantity of service provided increases. However, the delivery system is more directly affected by the characteristics of the area being served. The cost trade-offs between the two components will determine the cost of delivering water to any portion of the service area.

Few analytical instruments are available to study the economics of water supply systems. Therefore, EPA's Drinking Water Supply Research Di-

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vision initiated a program to develop techniques and methodologies to allow for the evaluation of regional economic impacts for water supply. This paper describes the development of a simulation model that is designed to aid in such an evaluation. The model will also assist in providing insights into other water related economic issues such as spatial pricing and costing, conservation policies, operating improvements versus increased capital expenditure, user class subsidization, and fire protection capacity (4,5).

The model, called the Water Supply Simulation Model (WSSM), incorporates a series of submodels to describe the various aspects of the economic, demographic, and hydraulic systems that make up a water utility. A report describing the model is available from the National Technical Information Service (5). The logic utilized in developing the model is considered in the following sections.

MODEL STRUCTURE

The WSSM is based upon the concept of a water utility as a network overlaid upon a spatial distribution of supply and demand. The model explicitly deals with the relationship of delivered water costs to the service requirements of spatially distributed demand. This spatial representation is based on a characterization of the water supply system as a link-node network. It is assumed that water enters and leaves the system only at nodes, which represent treatment plants, junctions, demand locations, and storage tanks. Water is carried between and among nodes through connecting links. Costs are allocated to the various facilities and system components based on flow in the system.

The WSSM requires that the system be described as a network of pipes, storage tanks, treatment plants, demands and other hydraulic elements. Information concerning the network is stored in a network data base, which also stores additional descriptive or calculated information about each element, such as size of pipe, geographic location of each demand, population associated with a demand, connectivity of pipes, etc. Certain basic information *must* be stored in order for the system to operate, but other information is elective, and is a function of the particular uses and analysis to which the WSSM is to be put. Other program modules communicate with the data base through standardized data base access methods, which consist of routines to extract or insert information into the network data base.

Fig. 1 shows the way in which the WSSM operates. Data are entered into the data base (Link and Node files) through an establishment module. Once the data base is established, various program modules manipulate it. The general elements of the WSSM are: The network data base; data base establishment and editing modules; data base access methods; hydraulic network analysis models; other physical/economic models; and display and reporting modules.

The two key modules in terms of system evaluation are the hydraulic and solver algorithms. The current version of WSSM uses both WATSIM and the "Wood Model" as the basis for hydraulic analysis (9,10). Both of these algorithms are standards available in the profession and are described elsewhere. The second module SOLVER is a general purpose

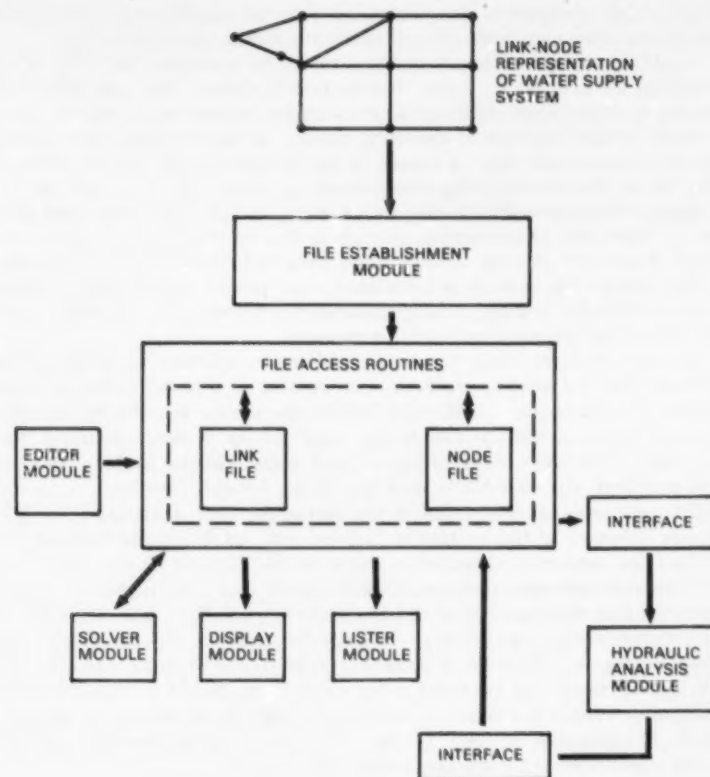


FIG. 1.—Basic Structure of Water Supply Simulation Model

algorithm that sets up and solves problems relating to mixing in networks, given the network topology and flows (7). It is used with WSSM for three generic types of problems: (1) Determining time required to travel from any source to a node (travel time); (2) determining the concentration of any constituent at any node, given the concentration of the constituent at all sources; and (3) determination of the cost of delivered water at any node, given the individual annualized costs associated with the nodes and links of the system. SOLVER is described briefly in the following section.

SOLVER ALGORITHM

Engineering analysis of water distribution systems is frequently limited to the solution of the hydraulic network problem, i.e., given the physical characteristics of a distribution system and the demands at nodes, the flows in links and the head at all nodes of the network are deter-

mined. This problem is formulated as a set of simultaneous nonlinear equations, and a number of well-known solution methods exist.

In addition to the hydraulic analysis problem, however, there are other problems of interest in water distribution systems. The calculation of mixing of water from different sources in the system is of concern, particularly where sources of different quality of water may exist. Calculation of travel time from a source to any demand node in the network may be of use in analyzing water-borne disease outbreak data, or examining time-dependent quality parameters, such as trihalomethane levels. A third area of increasing interest is that of economic analysis and "cost of service" pricing, in which the allocated cost of water to various points within the system is calculated, and priced accordingly (similar in concept to the pricing of long-distance telephone calls, or airline tickets, based on distance and volume of use).

For each of these three types of problems, a solution variable can be defined. For the mixing problem, the variable of interest is the concentration of a particular constituent within the water. For the travel time type of problem, the variable is the "age" of the water, assuming that the water is of some defined age at each source in the system. For the cost problem, the variable is unit cost (e.g., \$/cubic foot/sec).

The problems are formulated by assuming that a steady-state hydraulic solution of the system is known, i.e., all flows throughout the system are known and satisfy a mass balance at the nodes. Then, as each element of water proceeds from a source to a demand node, it may undergo a transformation as it passes along each link, and at nodes is mixed with water from other portions of the network. By assuming complete mixing at each node, a linear equation in the intrinsic variable and the known flows can be written for each node, based on conservation principles. With the unknown boundary conditions at sources to the network, N equations in each of the N unknown nodal variables can be written and solved by standard methods.

By appropriate definition of the variables, a general formulation for each of the three generic types of problems (concentration, travel time, and cost) can be developed.

Each of the three types of problem can be represented by similar equation forms. For the concentration problem, there is neither a link- or node-associated additive value. For the travel time problem, there is a link-associated added value (the link travel time), and for the cost problem, there are both link- and node-associated fixed cost values. A more complete analysis of this approach is presented elsewhere (7).

The general formulation at any node i , for all three types of problem, can be expressed as

$$P_i = \frac{\left[\sum_j \{Q_{ij} * P_j\} + \{d1 * LV_{ij}\} + \{d2 * NV_i\} + \{S_i * SP_i\} \right]}{I_i} \dots\dots\dots (1)$$

where the sum is taken for all j such that flow is from j to i , and: P_i = appropriate node-related parameter; LV_{ij} = corresponding link-associated value for link ij (cost and travel time solution); NV_i = corresponding

node-associated value for node i (cost solution); S_i = external source flow into node i ; SP_i = external boundary condition parameter value at node i ; $d1 = 0$ for concentration problem and 1 for cost and travel time problems; $d2 = 0$ for concentration and travel time problem and 1 for cost problem; I_i = total inflow to node i ; and Q_{ij} = flow from node j to node i .

NUMERIC EXAMPLE

A simplified network can be used to demonstrate the manner in which the equations are set up. Assume a two-source network consisting of 5 links and 4 nodes, as shown in Fig. 2. It is assumed that the flows have previously been determined by a hydraulic analysis, such that continuity is maintained at all nodes. The link-associated flows, flows from the two external sources, and the node demands, are shown in Fig. 2. The concentration case is illustrated below, assuming that the concentration at source 1 is SC_1 , and the concentration at source 2 is SC_2 . Observing the flows at each node, and the associated flow directions, then the following equations can be written for each of the four nodes:

$$C_1 = \frac{(F_1 * SC_1)}{F_1} \dots \dots \dots (2)$$

$$C_2 = \frac{(F_3 * C_1 + F_8 * C_3)}{F_3 + F_8} \dots \dots \dots (3)$$

$$C_3 = \frac{(F_{11} * SC_2)}{F_{11}} \dots \dots \dots (4)$$

$$C_4 = \frac{(F_4 * C_1 + F_7 * C_2 + F_9 * C_3)}{(F_4 + F_7 + F_9)} \dots \dots \dots (5)$$

Thus, there are four equations in four unknowns that can be solved given the known values of the boundary conditions, SC_1 and SC_2 . In

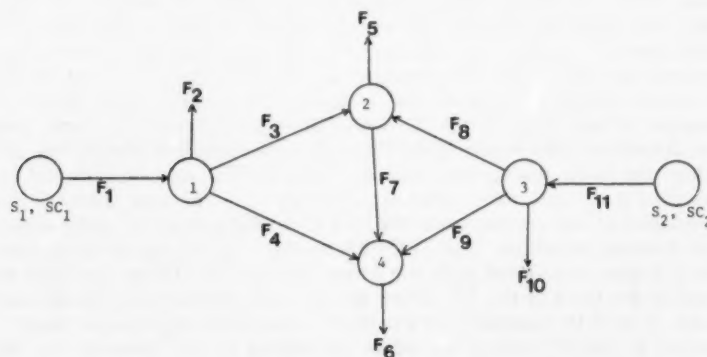


FIG. 2.—Example Problem

this simplified case, these equations can be solved by direct substitution, whereas in more complex cases, matrix methods are applied.

IMPLEMENTATION OF SOLVER

The formulation previously considered has been implemented as a Fortran program in conjunction with the Water Supply Simulation Model (WSSM). Within the WSSM, a data base of node and link-associated information (such as flow, cost, etc.) is maintained. The SOLVER module as implemented in the WSSM sets up the coefficient matrix as defined by Eq. 1, based on user input that describes which of the three types of problems is being addressed, and where in the data base the Q_n , LV_n , NV_n , S_i , and SP_i values are to be found. SOLVER then proceeds to solve these equations, using a sparse-matrix solution code developed by Chandrashekar (2). The resultant node-associated P_i values are stored in the data base, and are then available for further calculation, or display as a numerical, shaded, or contour map. The data-base orientation of the WSSM means that, once the appropriate data has been stored in the WSSM data base, a run of SOLVER can be specified with only a small number of input items (typically only 5 storage locations in the data base, and external SP_i boundary conditions for each of the external source nodes).

NONSTEADY-STATE MODELING

The SOLVER algorithm has been developed for steady-state analysis. Storage tanks present a particular problem because they may be in one of three states: Filling; discharging; or floating on the system. Tanks that are considered to be filling in a given scenario do not pose a particular problem in using SOLVER nor do tanks that are floating on the system. Tanks that are discharging into the system must be handled in a special way.

The SOLVER algorithm considers any node at which water enters the system from other than an upstream link to be an external source, that must have a correspondingly-specified SP_i . Water in tanks, however, does not come from a true "external" source—rather, it is water that some previous time passed through the network, originating at the true external sources. Thus, for example, in the travel time solution, water in a tank that discharges to the system has a certain "age," that is a function of how long it took the water to originally reach the tank, and the detention time in the tank. Thus, it is necessary to define the SP_i values for tanks discharging into the system. This can be handled by developing a "tank fill" hydraulic scenario, i.e., one that portrays the hydraulics of the system when the tanks are filling (such as a late night, low demand situation). The SOLVER module can be run to determine the P_i values associated with the filling tank nodes. These can then be used as the basis of the SP_i values for the tank-discharge hydraulic scenario. It may be necessary to externally determine appropriate modifications to the SP_i values for tanks developed in this manner, as, for example, to handle detention time in tanks between the "tank fill" and "tank discharge" scenarios. For the cost solution, some cost/value must

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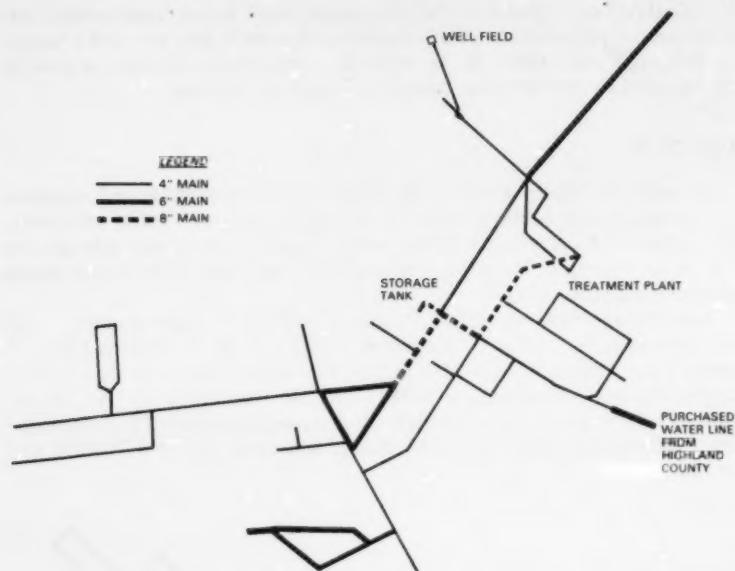


FIG. 4.—New Vienna System Schematic

Water is supplied to the system from two sources: (1) A well field and treatment plant, operated by the Village; and (2) purchased water from Highland County. The Village is required to purchase a set amount of water each month from Highland County, and operates so as to purchase that amount of water, then switches over to its local sources. In any month, typically two-thirds of the water will be purchased. Both sources do not operate simultaneously.

The distribution system consists of pipes 8 in. and under, with the majority being 4 in. in diam. The system dates back to 1903. A single elevated storage tank, with a capacity of 50,000 gal, serves the system to provide load leveling and minimal fire protection. Additional storage is required, and plans are under development to provide this capacity. The current system operates based on the level in the storage tank. The system is shown schematically in Fig. 4.

The elevations in New Vienna range from approximately 1,110 ft–1,180 ft. The average total head for the overall system is approximately 1,240 ft. Low pressure in the range of 23 psig exist in the higher elevation portions of the village during normal operating situations, and under firefighting situations, pressures may drop as low as 0–12 psig in certain areas.

DATA BASE DEVELOPMENT

Development of the New Vienna Data Base consisted of the following steps:

1. Delineation of the system in link-node form.
2. Determination of physical system characteristics (pipe size, diameter, etc.) and spatial coordinates.
3. Development of demand data.
4. Development of cost data.

There is, of necessity, some interplay among these efforts to insure that the link-node representation does portray the important changes in physical system character.

DELINEATION OF SYSTEM IN LINK-NODE FORM

A link-node representation of the New Vienna water system was laid out on a gridded overlay to the 1 in. = 200 ft base map. Nodes were located in continuous lengths of pipe, based on their serving as centers of aggregation of demand. Major changes in pipe direction, at pipe junctions, and changes in pipe diameter or type. Each link and node was numbered sequentially. The New Vienna link-node representation consists of approximately 50 links and 50 nodes and is shown in Fig. 5.

The coordinate locations of each node were digitized through hand take-off from the gridded overlay, and recorded. Elevations were obtained by placing the overlay on the base map, and reading the elevation at each node from the contours on the base map. (Contours on the base map are at 3 ft intervals). Data for both the links and nodes were encoded, and prepared as input to the file establishment module of WSSM.



FIG. 5.—New Vienna Node-Link Representation

DEVELOPMENT OF DEMAND DATA

While metered information is available for the majority of the Village, demand data were developed for other than industrial users, by performing "house counts" within demand zones. Demand zones were drawn on the link-node overlay, to associate demands with nodes. Each node has a demand zone, and it is assumed that any demands falling within that area are aggregated to the node.

DEVELOPMENT OF COST DATA

The economic allocation procedure requires a single annualized cost, representing the combination of amortized capital and O&M costs, for each node and link. For the case of New Vienna, actual construction cost was not available for most elements (11). Therefore, estimates of current cost were made and deflated to the estimated original cost by use of the three digit Engineering News Record Construction Cost Index. The existing well water treatment system costs were estimated based on cost curves derived from the publication "Estimating Water Treatment Costs" (6). Bid data for replacement of the elevated storage tank was used to estimate its replacement cost. For capital cost, an assumption of 10% interest and 20 yr amortization period was used.

Annual O&M costs are taken from Village records. Total 1981 cost, including O&M debt service and administrative costs, was projected to be \$46,721. Nodal and link annual cost summaries showing the 1981



FIG. 6.—Cost Contours (cents/1,000 gal) for New Vienna (Scenario 1)

construction cost, year of construction, CCI factor, original construction cost (computed), and 1981 O&M cost were calculated. From these annual costs and flows, unit costs were calculated.

Four hydraulic "scenarios" were developed, representing four conditions of flow within the network of interest, as follows:

Scenario I—Discharge to system from locally-owned treatment plant and tank.

Scenario II—Tank filling from treatment plant source.

Scenario III—Discharge to system from purchased water and tank.

Scenario IV—Tank filling from purchased water source.

Scenarios I and III were the two cases of interest in determining alternative cost of service. Scenarios II and IV were used, as aforementioned, to develop costs to be allocated to water in the tank. The SOLVER algorithm was used to develop and store cost of service, and for this example, a unit cost in cents/1,000 gal basis, for both Scenarios I and III was calculated. Other utilities within WSSM were used to develop the cost differential between the two scenarios at each node, and this was displayed in the form of a contour map showing cost differential contours. A contour map representing the unit costs associated with Scenario I is shown in Fig. 6.

SUMMARY AND CONCLUSIONS

The development of a spatially oriented water supply simulation model has been described. The model can be used to provide spatial cost allocation, time of travel, and contaminant concentration information in a water supply network. Development of this model provides a tool with which to acquire additional insight into the treatment and delivery of water. The approach employed in the WSSM is general in nature, and is not restricted to water supply problems—in fact, it should find wide applicability in analysis to a variety of kinds of service delivery systems that can be characterized as a distribution network overlaid on some spatial distribution of supply and demand.

It should be re-emphasized that WSSM does not in and of itself provide answers. It is, rather, a tool for managing and displaying water supply network data. The WSSM technology is designed to aid the researcher, engineer, economist, or planner in a variety of ways, but in no sense can one "wind it up and let it give you the answers."

ACKNOWLEDGMENTS

Many people contributed to the development of the WSSM. Dr. Richard Stevie performed much of the early work on the original implementation of WSSM. Mr. A. Lee Cesario of the Denver Water Board, and Mr. Bruce Burbank of the Public Service Company of Colorado, provided advice, assistance, and access to their versions of the WATSIM hydraulic analysis model. Dr. M. Chandrashekar of the University of

Waterloo, Ontario, graciously allowed the use of subroutines developed by him to be incorporated as the sparse matrix simultaneous equation solution techniques utilized in the System solver module of the WSSM. The contributions of these individuals have been of significant benefit to the development of the WSSM.

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APPENDIX II.—NOTATION

The following symbols are used in this paper:

- C_1 = concentration at node 1;
- C_2 = concentration at node 2;
- C_3 = concentration at node 3;
- C_4 = concentration at node 4;
- $d1$ = zero or one variable;
- $d2$ = zero or one variable;
- F_1 = flow into node 1;
- F_2 = flow out of node 1;
- F_3 = flow out of node 1 into node 2;
- F_4 = flow out of node 1 into node 4;

F_5	=	flow out of node 2;
F_6	=	flow out of node 4;
F_7	=	flow out of node 2 into node 4;
F_8	=	flow out of node 3 into node 2;
F_9	=	flow out of node 3 into node 4;
F_{10}	=	flow out of node 3;
F_{11}	=	flow into node 3;
I_i	=	total inflow to node i ;
$i, j, k, \text{ and } x$	=	node indices;
LV_{ij}	=	link-associated value for link ij ;
NV_i	=	node-associated value for node i ;
P_i	=	appropriate node-related parameter (cost, age, concentration);
Q_{ij}	=	flow from node i to node j ;
S_1	=	external source flow into node 1;
S_2	=	external source flow into node 3;
S_i	=	external source flow into node i ;
SC_1	=	constituent concentration in external source flow at node 1; and
SC_2	=	constituent concentration in external source flow at node 2.

NOTICE

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